IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

ELECTRON COOLING FOR THE FERMILAB $\bar{p}$ SOURCE

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SUMMARY

Electron cooling will be used to cool and accumulate antiprotons in the Fermilab $\bar{p}$ source. Successive $\bar{p}$ production cycles will be injected into the cooling ring with offset momentum, and coalesced into the stack using longitudinal electron cooling. The stacking performance of electron cooling is evaluated. It is shown that optimum $\bar{p}$ accumulation rate is obtained by increasing the cooling energy until the cooling time just matches the cycle time τ_o for $\bar{p}$ production. For Fermilab Tevatron I this corresponds to $T_{\bar{p}}$ = 1.5 GeV, T_e = 750 keV. The main features of the electron beam design are described. For a primary electron beam current I_e = 10A, we expect a loss current (to ground) $I_\ell \lesssim$ 10mA and a transverse temperature $T_\perp \sim$ 0.25 eV.

I. Introduction

The Tevatron I program at Fermilab has as its goal $\bar{p}p$ colliding beams at $\sqrt{s}$ = 2 TeV. At the heart of the program is the antiproton source. $\bar{p}$'s are produced at T_o = 4.5 GeV by collisions of 80 GeV protons from the Main Ring. The antiprotons are injected into a Precooler ring, using momentum stacking. The momentum spread of the beam is cooled by a factor ~5 using filter stochastic cooling . The beam is then decelerated to T_1 = 2.5 GeV. The original Schottky bandwidth is restored by the increase in $\eta = \gamma^{-2} - \gamma_t^{-2}$. The momentum spread is again cooled by a factor 5. The beam is again decelerated to T_2 = 1.5 GeV to restore the original Schottky bandwidth. The momentum spread is cooled by a third factor 5. The antiprotons are now ready for transverse cooling and accumulation. The precooling sequence described above takes ~2 sec per cooling step, for a total time τ_o = 8 sec. The final momentum spread at T_2 has been decreased by a factor 50.

Final cooling and accumulation of the antiprotons is done in a separate fixed-energy storage ring. We must accumulate ~1000 $\bar{p}$ production cycles in order to achieve the design luminosity L = 10^{30} cm^{-2} sec^{-1} . Electron cooling is ideal for this purpose because it can quickly cool a non-relativistic beam, with a damping rate that is independent of stored intensity. Stochastic cooling, on the other hand, uses statistical fluctuations of the ensemble as signal; its damping rate is inversely proportional to stored intensity.

The choice of energy T_3 for the Accumulator Ring is obviously important. The transverse acceptance of the $\bar{p}$ source is limited by the Precooler aperture at the low-energy end of its cycle. This consideration dictates that T_3 be as large as possible, consistent with a damping time $\tau \leq \tau_o$.

In Section II, we calculate the damping time for $\bar{p}$ accumulation, taking care to expose all energy dependences. This analysis provides a basis for choosing the electron cooling energy. The electron beam design is discussed in Section III.

II. Electron Cooling for Accumulation

Antiprotons are injected into the Accumulator on an off-momentum orbit, and then coalesced into the stack using electron cooling. Cooling takes place in all phase space dimensions. The momentum cooling rate $\vec{F}_\parallel$ is the quantity of interest in choosing a cooling energy. The new $\bar{p}$ beam must be coalesced into the stack in one precooler cycle τ_o .

Figure 1 shows the velocity distribution $\beta_\parallel$, $\beta_\perp$ for the antiprotons and the electrons in the rest frame. These velocities are defined by

$$\begin{aligned} \beta_{e\perp} &= \sqrt{2T_e/mc^2} \sim 10^{-3} \\ \beta_{e\parallel} &= e\,\delta V/\beta\gamma mc^2 \sim 10^{-5} \\ \beta_{\bar{p}\perp} &= \beta\gamma\theta \\ \beta_{\bar{p}\parallel} &= \beta\,\delta p/p \end{aligned} \qquad (1)$$

In the analysis that follows, we will suppose that initially

$$\beta_{e\perp} \ll \beta_{\bar{p}\perp} \quad , \quad \beta_{e\parallel} \ll \beta_{\bar{p}\parallel} \quad , \quad \beta_{\bar{p}\parallel} \lesssim \beta_{\bar{p}\perp}$$

The drag force is[2]

$$\vec{F} = \frac{-4\pi e^4 \mathcal{L} n}{mc^2}\left(\frac{L}{C}\right)\frac{\vec{\beta}_{\bar{p}}}{\beta_{\bar{p}}^3} \qquad (2)$$

where n is the electron density, (L/C) is the fraction of the ring being cooled, and $\mathcal{L}$ is the Coulomb logarithm. This corresponds to a damping rate

$$\lambda = -\frac{3F_\parallel}{\delta p} = \frac{12\pi e^4 \mathcal{L} n}{mM\gamma^2 c^3}\left(\frac{L}{C}\right)\frac{1}{\beta_{\bar{p}}^3} \qquad (3)$$

Now let us make explicit the energy dependence of each of the quantities in Equation 3. Defining the e-beam size in the cooling system to be a, the electron density is

$$n = i/\pi a^2 \beta\gamma c e \qquad (4)$$

The transverse beam size is limited by the acceptance ϵ of the precooler. With a lattice function β_ℓ in the cooling system, the transverse beam size a is

$$a = \sqrt{\beta_\ell \epsilon/\pi} \qquad (5)$$

The rms angle is

$$\theta = \sqrt{\epsilon/6\pi\beta_\ell} = \frac{\epsilon}{\sqrt{6}\,\pi a} \qquad (6)$$

Since λ is proportional to the length L of the cooling system, we choose L = β_ℓ as a practical limit. This yields

$$\lambda = k\frac{i\,a^3}{\beta^4\gamma^4 C\,(\epsilon/\pi)^4} \quad , \qquad (7)$$

$$k = \frac{12\times 6^{3/2}\, r_e r_p \mathcal{L}}{e} = 7\times 10^{-11}\ \mathrm{M^2/Coulomb}$$

Practical electron beam parameters are i = 10A, a = 2.5cm. The Accumulator circumference C scales with momentum: C = $\beta\gamma C_o$, where $C_o \sim$ 90m for a practical lattice. The Precooler acceptance is $\epsilon \sim 50\pi 10^{-6}$ m. Requiring a damping time τ_o = 8 sec, we obtain the condition

$$\beta^5\gamma^5 = 155 \quad , \quad \gamma = 2.8$$

The Accumulator parameters are then $T_3 = T_2$ = 1.5 GeV, C = 205m, β_ℓ = L = 12m.

We now return to the assumptions following Equation

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1. The initial rest frame transverse velocity is

$$\beta_{\bar{p}_\perp} = \beta\gamma\theta = 2\times 10^{-3}.$$

The momentum acceptance of the Precooler is ~4%, so the pre-cooled rest frame longitudinal velocity is $\delta p/p \simeq 8 \times 10^{-4}$. The fresh beam is injected on an off-momentum orbit, so

$$\beta_{\bar{p}_\parallel} \simeq 2.5\beta\,\delta p/p = 2\times 10^{-3}$$

Thus the initial assumptions are justified.

The invariant emittance of antiprotons accepted in the cooling system is

$$\epsilon_o = \epsilon\beta\gamma = 115\pi\, 10^{-6}\, m.$$

This corresponds to an increase of a factor 3.4 in $\bar{p}$ accumulation over the design using accumulation at T_3 = 200 MeV.

II. Electron Beam Design

The electron beam parameters for cooling at $T_{\bar{p}}$ = 1.5 GeV are given in Table I. The gun is shown in Figure 2. It has immersed-field Pierce geometry, with uniform magnetic guide field. An electrostatic lens triplet (1,2,3 Figure 2) allows tuning for quiescent transverse temperature ($T_\perp$~0.25 eV). The main acceleration takes place in a uniform-gradient column. The Larmor excitation in the toroid-solenoid transitions is resonantly cancelled. Clearing electrodes are provided for removing slow electrons trapped in the beam.

The optics of the gun and column geometry is shown in Figure 2. Also shown is a parametric plot in (β_x, β_y) of the life history of a ray near the edge of the beam, Figure 3.

The collection process will be arranged as in the present Fermilab design. The beam is decelerated to V_e~few kV upstream of the collector anode, then gently reaccelerated into the collector. Residual gas ions are trapped in the anode region, and neutralize the electron space charge. The resulting equipotentials form a virtual grid which retards backscattered electrons from being reaccelerated. In this way we have suppressed beam losses (which must be supplied from ground) to the level of ~5×10^{-4}. For a primary beam current of 10A, the high voltage power supply must be capable of delivering~20mA. Cockroft-Walton stacks with this capability are routinely available today.

In summary the design and construction of the 750kV, 10A electron beam required for the $\bar{p}$ source appears to be quite feasible. The optics and high voltage aspects have been researched in detail, and work will soon begin on hardware.

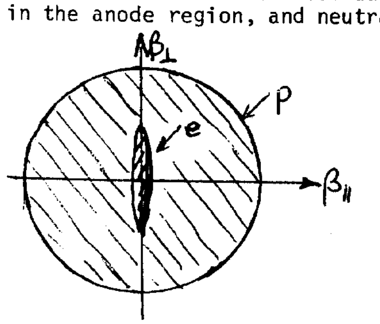

Figure 1. Velocity distributions of electrons and antiprotons before cooling.

TABLE I
Parameters of the Electron Beam

Energy	750	kV
Current	10	A
Temperature	0.25	eV
Cooling Length	12	m
Guide Field	1.5	kG
Beam Diameter	5	cm
Loss Current	10	mA
$\bar{p}$ Lattice β_ℓ	12	m
Damping Time	8	sec

References

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2. W. Kells et al., Proc. of the XIth Int. Conf. on Part. Acc., p 814 (1980).

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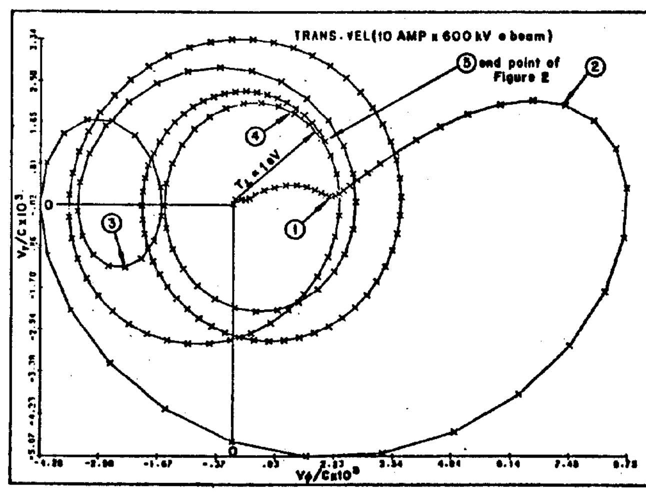

Figure 3. Parametric plot in (v_r, v_ϕ) of the life history of a peripheral ray.

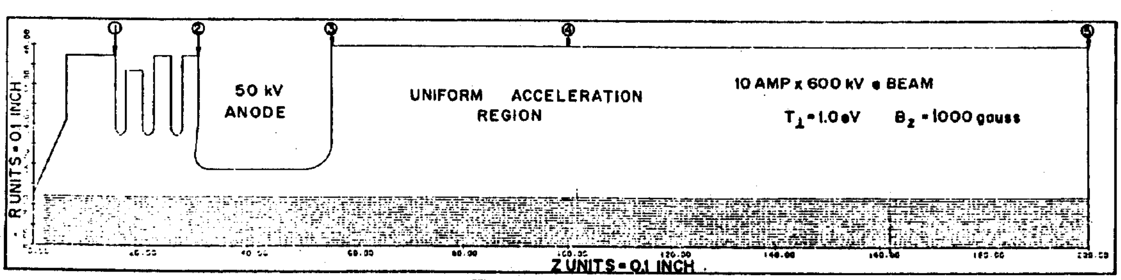

Figure 2. Calculated trajectories in the gun design (750 kV, 10 A)